PERSPECTIVE

Epidemics and the future of coffee production

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In this perspective, we draw on recent scientific research on the coffee leaf rust (CLR) epidemic that severely impacted several countries across Latin America and the Caribbean over the last decade, to explore how the socioeconomic impacts from COVID-19 could lead to the reemergence of another rust epidemic. We describe how past CLR outbreaks have been linked to reduced crop care and investment in coffee farms, as evidenced in the years following the 2008 global financial crisis. We discuss relationships between CLR incidence, farmer-scale agricultural practices, and economic signals transferred through global and local effects. We contextualize how current COVID-19 impacts on labor, unemployment, stay-at-home orders, and international border policies could affect farmer investments in coffee plants and in turn create conditions favorable for future shocks. We conclude by arguing that COVID-19's socio-economic disruptions are likely to drive the coffee industry into another severe production crisis. While this argument illustrates the vulnerabilities that come from a globalized coffee system, it also highlights the necessity of ensuring the well-being of all. By increasing investments in coffee institutions and paying smallholders more, we can create a fairer and healthier system that is more resilient to future social-ecological shocks.

COVID-19 | Hemileia vastatrix | plant diseases | social environmental systems | coffee

Coffee is one of the most widely traded agricultural commodities in the world, supporting the livelihoods of ∼100 million people globally (1). In 2014 alone, an estimated 26 million farmers in 52 countries cultivated more than 8.5 million tons of coffee, accruing a value of US$39 billion in those countries (2). The retail value of coffee is significantly higher, with sales reaching as much as $87 billion in the United States in 2019 (3). Smallholder farmers, typically with landholdings of 5 ha or less, dominate production across most of the main cultivation regions.

Despite coffee's economic importance to low-income countries around the globe, the industry has for decades struggled with numerous long-standing stressors and sudden shocks, including institutional reforms, market price volatilities, extreme climate events, and plant diseases and pests (4–6). The global coffee industry, as is true for all segments of society, is now responding to the COVID-19 pandemic. The epidemiolocal risk to coffee production is substantial, but not only in its public health risk. As a result of structural vulnerabilities within coffee systems, COVID-19 is also a potential trigger for renewed epidemics from a pernicious plant disease, coffee leaf rust (CLR). CLR is the most important disease of *Coffea arabica* in the world and the only significant coffee disease with a global distribution (7–9).

The 2012 CLR epidemic across Latin America and the Caribbean (LAC) serves as a cautionary example

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of the fragility of the coffee production system. One of the outbreak's roots can be traced to the 2008 global recession that drove significant declines in global coffee demand (5, 10). This, in turn, forced many coffee farmers across LAC to reduce investment in or abandon their coffee fields altogether. By the time the global coffee sector started to rebound in 2012, unchecked CLR was present and becoming severe on many farms in LAC. Ultimately, CLR devastated coffee production across LAC at a severity that had not been seen in the last 150 y, when the first CLR epidemic was recorded in Ceylon in the 1870s (11). The present COVID-19 pandemic is yet another challenge to the global coffee industry. This time, however, the consequences could be greater due to the state-sanctioned lockdowns and restrictions in labor mobility, a global recession, and the potential drawn-out impacts from cascading effects like CLR.

In this perspective, we draw on recent scientific research on CLR to explore how the socioeconomic impacts from COVID-19 could lead to the reemergence of another CLR epidemic. We describe how past CLR outbreaks have been linked to reduced crop care and underinvestment in coffee farms, as evidenced in the years following the 2007 to 2009 global financial crisis. We discuss relationships between CLR incidence, farmer-scale agricultural practices, and economic signals transferred through global and local effects. We contextualize how current COVID-19 impacts on labor, unemployment, stay-at-home orders, and international border policies could affect farmer investments in coffee plants. And we conclude that COVID-19's socioeconomic disruptions are likely to drive the coffee industry into another severe production crisis. While this argument illustrates the vulnerabilities that come from a globalized coffee system, it also highlights the necessity of ensuring the well-being of all. By increasing investments in coffee institutions and paying smallholders more, we can create a fairer and healthier system that is more resilient to shocks.

Biology and Life Cycle of CLR

Coffee rust is caused by the fungus *Hemileia vastatrix* in the order Pucciniales (rust fungi), which evolved approximately 15 Mya to infect species of *Coffea* in the paleotropics (12). In contrast to almost all other fungal plant pathogens, rust fungi are obligate biotrophic pathogens, which means they need a living host to survive and are incapable of reproduction without one (13). Like many plant pathogenic fungi, the rust fungi reproduce both sexually and asexually. But, unlike other plant pathogens, they do so through a complex life cycle that contains up to five different sporulating stages to complete (14).

The *H. vastatrix* life cycle is incompletely known, but the most important spore stage for causing epidemics is the urediniospore stage. The disease cycle begins by infection of a microscopic urediniospore that enters the host via stomata or leaf pores, located on the underside of the leaf (15). After entering, the germinating urediniospores colonize neighboring host cells to obtain nutrients, eventually killing those cells while producing the next crop of spores. The new spores are produced in a structure called a uredinium and forced through the stomata, where they are dislodged primarily by rain. Wind, rain, animals, or people carry them to new leaves, beginning infection anew. The time from the initial infection to the production of a new sporulating uredinium is about 4 to 7 wk (16). A single urediniospore is capable of producing four to six generations, with exponential increase of tens of thousands of spores generated from the initial single infection (17).

All parts of this uredinial cycle depend on environmental conditions. Urediniospore germination requires nearly 100% humidity, and rain is the primary dispersal mechanism for spores. The time from initial infection to the production of a new sorus is shortened in higher ambient temperatures. Thus, drier, cooler climates are not conducive for CLR spread, whereas warmer, wetter climates favor an increase of urediniospores. CLR levels typically peak during harvest periods when plants focus their resources on fruit growth, and because CLR spores can be spread from tree to tree within individual plots and from farm to farm by harvesters (18). Additionally, management practices that limit host genotypic diversity, such as monocultural plantings of single coffee cultivars, favor the selection of more virulent *H. vastatrix* genotypes (see for example, refs. 19 and 20).

CLR's principal effect is defoliation, which reduces the plant's photosynthetic activity. This affects the quantity of the fruit and can impact the quality of the coffee. CLR only kills the plant in severe cases, but plants usually bear less fruit for several years after intense epidemics (5, 16). When CLR reemerged in Central America in 2012, production declined by 10% and by ∼20% in the following year (21). The reduction in the second year was due in part to the decrease of the productive area as severely affected plots were either rejuvenated or renovated (22).

Main Drivers of Coffee Rust

The drivers of CLR, like all plant diseases, are caused by complex interactions between a pathogen, a host, and the environment. The effect of human actions on each of these is substantial. In this section, we describe the main factors shaping CLR development and spread (see *SI Appendix*, Fig. S1 for an illustration of the main causative factors and feedbacks commonly discussed in the scientific literature). We emphasize that CLR needs to be understood as an integrated socioenvironmental phenomenon: CLR and its impacts result from the relationships between weather and climate, pathogen characteristics, coffee tree characteristics, and human decision-making, institutions, markets, and investments in farm design and management (10, 23).

Environmental Drivers of Coffee Rust. Environmental factors influencing CLR development include temperature, dew, rainfall, solar radiation, and wind. Their influences are felt at different stages of the disease life cycle in sometimes countervailing ways (23, 24). For example, prevailing weather conditions appear to have been an important determinant of the Central American rust outbreaks. The 2012 epidemic in Central America was marked by above-average rain during the dry season and early stages of the rainy season that may have maintained a high level of initial inoculum. Below-average rain then followed at the end of the growing season, likely reducing the number of spores washed away by rains and thus increasing the quantity available for new infections. There are other possible interactions between weather and CLR, like reduced diurnal temperatures that can shorten the latent period of the disease (5), an increase in canopy wetness that increases infection risk (5, 25, 26), and the transportation of spores by wind that spreads infection (5, 27). Yet, the high-intensity epidemics in Colombia between 2008 and 2011, in Central America, Mexico, and the Caribbean in 2012, and in Peru and Ecuador in 2013, each had different meteorological regimes (5), underscoring the multidimensional causal pathways for CLR epidemics. Additionally, longer-term changes in temperature and rainfall believed to be associated with climate change have also been identified as possible contributors to the recent spikes in CLR incidence (e.g., ref. 24).

CLR also takes root as an indirect function of coffee plant phenology (especially at the varietal level) and cropping practices. *C. arabica*, known as Arabica coffee, is a more susceptible species than *Coffea canephora*, commonly known as Robusta coffee. Furthermore, different varieties and cultivars of Arabica possess different intrinsic resistances (16, 28). At the same time, CLR vulnerability is a function of plant health, with nutrient-deficient trees more susceptible to the disease. CLR disease development can therefore be controlled through cropping practices that enhance plant health (29) and that restrict pathogen development. The latter can be achieved through pruning, shade management, and by enhancing conditions for natural enemies like the mycoparasite fungus *Lecanicillium lecanii* (29, 30), although these relationships are complicated.

Economic Drivers of Coffee Rust. The onset of past CLR epidemics has also been linked to economic and market constraints. The links relate to the underlying structures of the political economy of coffee, the specific economic shocks that affect coffee production globally and at the national level, and the positive feedbacks that manifest among resource-constrained farmers who cannot afford to manage the disease.

As illustrative cases, all the reported high-intensity epidemics in Colombia and Central America since 1987 were concurrent with, or preceded by, periods of low international coffee prices or high input prices that reduced coffee crop profitability (5). The 2012 to 2013 CLR epidemics across LAC coincided with a period of significant coffee price declines, while the 2008 to 2011 Colombian rust epidemics were partly due to increases in input costs. With significantly reduced income, farmers had suboptimal coffee management, resulting in increased plant vulnerability to CLR and other pests and diseases. The global financial crisis of 2007 to 2009 may have exacerbated CLR incidence partly through increases in the cost of fertilizers (31, 32). Reduced fertilizer applications slow growth and leaf production, preventing plant recovery. Oil prices strongly determine fertilizer prices (33), and oil prices rose dramatically during the financial crisis due to factors including commodity speculation, OPEC (Organization of the Petroleum Exporting Countries) monopoly pricing, and supply–demand imbalances (34).

Wider changes linked to market reform and price regulations also set the conditions for CLR epidemics. The recent rust outbreaks across LAC have been labeled a neoliberal epidemic (11, 35) because the institutions that had long shaped the management of CLR were diminished or disbanded under neoliberal policies that advanced deregulation and free markets (36). In particular, beginning in the 1980s as neoliberalism took hold, international financial institutions such as the World Bank reduced the role of the state in regulating coffee markets (11). One consequence was a breakdown of the International Coffee Agreement (ICA) that set export quotas. As a result, global coffee prices have experienced systemic price volatility and prolonged periods of low prices (below the symbolic threshold of US$1 per pound of green coffee) due to imbalances between supply and demand (37). For example, coffee prices fell between 1989 and 1994 when producing countries, freed of quotas, put all stocked coffee on the international market. Later, in 2000 to 2005, prices crashed to new depths from a global oversupply driven mainly by production in Brazil and Vietnam (11). Since 2012, although international coffee prices have mostly been above the US$1 per pound, coffee crop profitability has fallen substantially due to the increase of production costs (38). In many countries, revenues periodically fell below costs, impoverishing many producers and impeding farm management and investments to defend against CLR and other risks.

Shortly after the end of ICA's quotas in 1989, national coffee agencies in Latin America succumbed to similar pressure from international financial institutions and their role in regulating financing and marketing production was greatly curtailed (39). Low coffee prices, austerity politics, and reduced production due to CLR impacts have weakened these institutions, which used to offer essential expertise in research and extension (11, 32).

For resource-constrained smallholder coffee farmers, the combination of underlying structural vulnerabilities and specific economic shocks makes them more susceptible to CLR. Specifically, reduced plant care in the years preceding CLR outbreaks and farmers' inability to afford inputs to control the spread of the rust, as well as the labor for proper management, have been identified as contributing factors for the epidemic. Economic shocks have been compounded by aging coffee trees, with lower productivity and higher susceptibility to the pathogens. Coffee plantations in El Salvador, for example, have not been able to recover production levels since 2012, largely because resources are scarce and many coffee stands are old (40). The cost of replacing old stands with new ones is prohibitive for many farmers due to the high upfront expenses and because it takes 3 y or more for new plants to produce a sellable crop.

In totality, the combined effects of low farmgate prices, increasing input costs, insufficient credit, and aging coffee plants have been persistent and common barriers for farmers to control CLR. Furthermore, global market booms and busts occur with less regulation to dampen the volatility compounded by reduced support from coffee institutes and state agencies. Thus, many coffee farmers subject to these conditions often experience a self-reinforcing feedback loop in which falling profits lead to reduced plant care. This sets the conditions for CLR to proliferate, resulting in further loss and reduced profitability.

None of these factors operates independently. The drivers of CLR are complex and interconnected, thereby exerting a range of overlapping influences throughout the disease life cycle (4). The causal pathways for CLR epidemics are therefore contingent on the ways economic and meteorological forces influence farm-level crop management. Similarly, farm management decisions (including a general preference for Arabica varieties due to their higher market prices) also drive susceptibility to the disease. Thus, CLR needs to be understood as an integrated socioenvironmental phenomenon. This perspective views CLR and its impacts as a result of a web of interactions constantly adjusting to climatic and meteorological conditions, pathogen dynamics, coffee tree characteristics, market fluctuations, and human agency and decision-making (23).

Overview of Past CLR Epidemics. We now provide a brief overview of past CLR epidemics dating back to the mid-1800s to illustrate that CLR proliferates in part by the multiple and intersecting economic and environmental conditions under which coffee is produced, managed, and regulated.

H. vastatrix was first observed in 1861 around Lake Victoria in East Africa (41), although the fungus had been coevolving with *Coffea* species for millions of years (12). After this initial sighting, CLR rapidly spread across the globe in three waves (42). The first disease wave hit the Indian Ocean Basin and the Pacific region between 1870 and 1920, causing a destructive epidemic in Ceylon in the 1870s. Prior to the epidemic, Ceylon was the world's third largest coffee producer. Management practices then favored large, uniform plantations of Arabica in full sun in order to maximize yields (11, 32). These conditions helped pave the way for the establishment of *H. vastatrix* after its introduction. By the 1890s, 90% of coffee farms in Ceylon had been abandoned, triggered in part by production declines due to the rust epidemic but also due to the fallout in coffee prices in the early 1880s that saw many local farmers switch to cinchona, tea, and other crops (coffee production across most of the East Indies had also collapsed).

The second CLR wave occurred in the 1950s and 1960s following the expansion of coffee across West Africa. However, the economic impact of CLR was limited in this instance because the region produced mostly the CLR-resistant Robusta species. Where Arabica was grown, it caused severe losses at this time (42). Finally, CLR crossed the Atlantic Ocean in the late 1960s, and during the 1970s and 1980s it spread throughout the coffee-growing regions of the Americas. The disease was initially kept at manageable levels through chemical applications and, in some countries, pruning practices (as mentioned previously in the case of Brazil). While CLR outbreaks were reported in South and Central America in the 1980s (5), beginning around 2008 parts of LAC experienced a severe cluster of outbreaks now known as "the big rust" (43). By 2012, CLR incidence was recorded across Central America, the Caribbean, Ecuador, Peru, and Mexico on a level not seen since Ceylon (5, 43). The big rust epidemic was responsible for catastrophic crop losses on many afflicted farms. The results from the LAC epidemic are still being felt.

The recent wave of CLR epidemics across the LAC have triggered a growing body of scholarship, primarily rooted in the plant and biological sciences, to understand the factors that have contributed to the high disease intensity and spread. There is little evidence that the big rust was caused by the evolution of a new virulence in *H. vastatrix* (26, 31). Rather, the combination of more conducive weather patterns, changing climatic conditions (e.g., ref. 24), and recurring economic shocks appear to be responsible (5, 31). The disease intensity is a function of the ways these different driving factors intersect. CLR outcomes will therefore differ across geographic regions as the conditions that favor disease development change over space and time (44) (Fig. 1).

The impacts from CLR have been uneven for the reasons previously mentioned. However, as Fig. 1 highlights, countries like Brazil, Ethiopia, and Vietnam have not shown signs of devastating rust epidemics. Plausible explanations for these observations further add place-based nuance. In Vietnam, producers largely grow Robusta coffee, which unlike Arabica, displays a high resistance to *H. vastatrix*. In Brazil, on the other hand, low CLR incidence may be related to the vastly different production system, which relies on mechanization rather than small shareholder farming, and systematic deployment of fungicides. CLR also may have been contained because farmers in Brazil often prune every 2 y, which would lower the often-substantial losses that are observed in the year after an epidemic. For Ethiopia, coffee has a low yield and there is a negative correlation between fruit load and CLR incidence. Ethiopia is also hypothesized to be the center of origin of *C. arabica* and is therefore likely to contain a much higher genetic diversity in the host-plant populations than in world regions where coffee has been introduced. With climate being an important influence on the recent epidemics in the LAC, a greater genetic diversity in Ethiopia may buffer the crop against the selection and increase of rust variants that are better adapted to changing climate conditions. Thus, there are many context-specific reasons that determine the spread, or not, of CLR.

Consequences of COVID-19 on Coffee

We have argued that the drivers of CLR emanate from the environment, the plant, the pathogen itself, farmer behaviors, and the socioeconomic structures that define neoliberal policy. As the world endures and responds to one of the largest social and economic shocks in modern times, the COVID-19 pandemic raises questions about the near- and long-term outcomes of coffee production, and specifically what this might mean for future CLR epidemics.

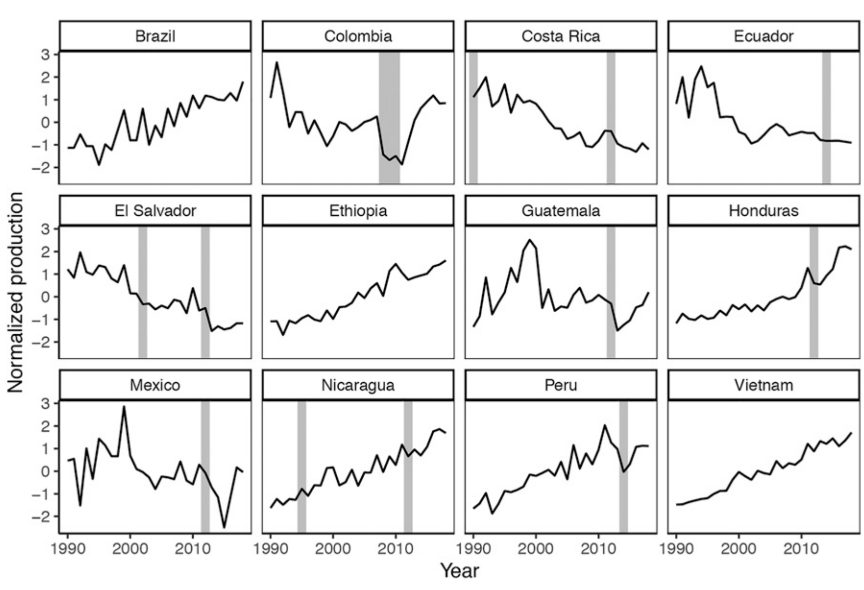

Fig. 1. Normalized total coffee production between 1990 and 2018 from major producing countries (International Coffee Organization data). Historical CLR outbreaks indicated in gray, from the literature (5, 43). Annual production data for each country from 1990 to 2018 were normalized to mean 0, SD 1.

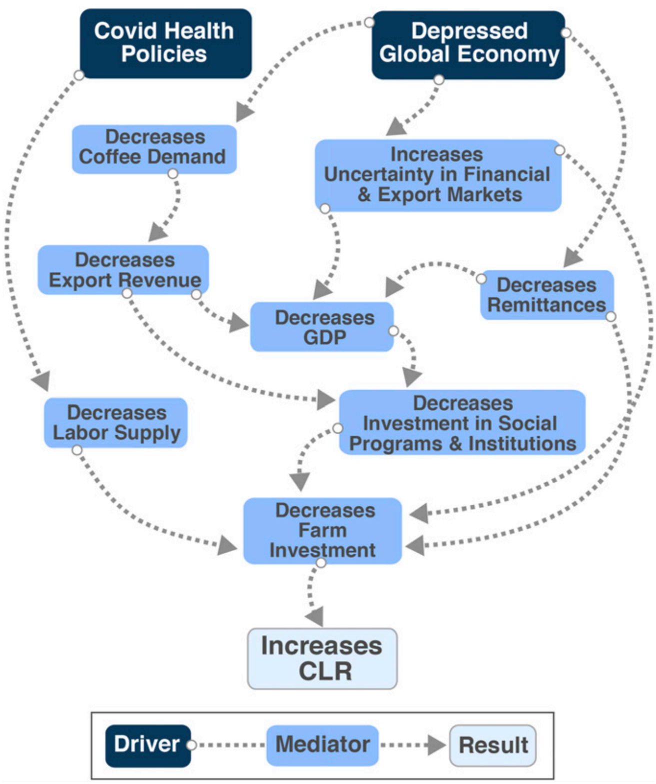

Fig. 2. **Impact pathways of COVID-19 on CLR. COVID-19 health policies and economic strain drive changes to mediating conditions that increase CLR. For example, a depressed global economy decreases remittances, which then decrease coffee farm investment and, in turn, increases CLR.**

As of late 2020, coffee harvest for 2020 to 2021 had yet to show a COVID-19 impact signal (45), and even a few forecasts that project slight increases in the global coffee production (45, 46). Notwithstanding these early indicators, there is ample reason to expect COVID-19 will generate widespread impacts that accentuate decades-old problems while also creating novel ones. In this section, we highlight two impact pathways (Fig. 2). They begin with changes at the national level in public health policies and declines in economic activity. Each pathway has ramifications for the investments across the coffee system, from institutions that support production to the coffee farmers who make investments in their farm. Specific impacts will depend on the resource endowments across all levels of the coffee system, with wealthier farmers better equipped to cope with the immediate impacts (32). But it bears stating that large-holders in many countries are also vulnerable through their dependence on seasonal labor that is subjected to movement restrictions between countries or even within a country as governments aim to curb the spread of COVID-19. Because nearly 80% of coffee produced on the global market is grown by small-scale farms, who typically have limited financial and physical capitals, Fig. 2 shows impacts will mostly resonate with this group.

One impact of public health policies enacted at the national level has been the restricted movement of people both nationally and internationally. The International Office of Migration reported that agricultural producers who rely on foreign workers to meet seasonal labor requirements face dramatic shortfalls in workers due to movement policies (47), as well as community and individual preferences to safeguard against health risks (48). Many coffee-producing countries rely heavily on migrant labor, especially during harvests. In Costa Rica, two-thirds of the coffee workforce is from border countries (49). By some estimates, more than 1.5 million people work in the coffee fields during Central American harvests, around five times the number of coffee farms. Given the crowded and poorly ventilated housing conditions farmworkers face in southern Mexico and Central America, the risk of COVID-19 transmission is high. As of the end of 2020, there was some indication that a lack of labor supply has affected harvests in South America (50), while some Central American countries had struck agreements to allow coffee migrants to cross international borders to avoid a supply shock (51). A reduction of labor supply could affect the amount of coffee harvested and raise wages. An increase to labor costs would more severely impact larger coffee plantations, where labor often accounts for more than half of total production costs in many countries (52). As profits decrease, farmers might be forced to leave some of the production unharvested, which may lead to increased incidence of diseases and pests, such as the coffee berry borer. While smaller farms rely more heavily on family labor, they too could be burdened by higher costs. Prolonged labor restrictions will likely translate into complex effects on production, income, and subsequent farm investment (48). Coffee price changes, coupled with other social and environmental changes, can have severe livelihood implications, including the temporary or permanent abandonment of coffee fields.

Rising unemployment across the globe has profound impacts on remittances, which in many countries are a critical source of income. In 2020, remittances are expected to fall by around 20% in LAC, 23% in Africa, and 22% in South Asia (53). The coffee-producing countries simply do not have enough capital to buffer the lost income through governmental social protection. The lower incomes will combine with other forces, such as food price fluctuations, which could worsen living conditions. As one outcome, food insecurity is likely to rise, especially among poorer households (54).

A second pathway could see a slowdown in global economic activities spurring lower global coffee demand, which is expected to fall in 2020 and beyond, depending on the time it takes for the global economy to recover. Historically, a 1% drop in global real gross domestic product (GDP) growth has been associated with 0.95% lower growth in global coffee demand (55). The GDPs for the United States, Japan, and euro area—the major coffee-consuming countries—are estimated to have declined between 3.6 and 7.4% for 2020; China grew an estimated 2% (56). Lower coffee demand will reduce foreign-exchange earnings. One projection for foreign-exchange losses across all export commodities in developing countries (excluding China) is around US$800 billion for 2020 (57). Additionally, global economic changes may increase farmgate price volatility and may contribute to devaluations of local currencies.

Approaches to Reduce CLR Impacts on Coffee Industry and Farmers

Existing Approaches to Combat CLR Directly. CLR, like other plant diseases, can be difficult to control. Resistant cultivars have long been considered the "silver bullet" practice to fight CLR. However, resistant cultivars are not often adopted at scale. Resistant varieties have been available in Colombia since the 1980s and in Central America since the 1990s. However, while the uptake of resistant varieties has been high in countries like Colombia and Honduras, their adoption has remained relatively low in other

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LAC countries. Several reasons may explain the low usage. Many specialty coffee buyers and some research institutes have been concerned about the quality of the resistant cultivars and did not recommend their use (5, 43). Growers have generally perceived the risk of CLR to be low (5, 11, 40), while also perceiving a higher risk of American leaf spot disease, another problematic fungal disease in Central America but one that preferentially attacks most of the CLR-resistant cultivars (40). And, as mentioned in *Economic Drivers of Coffee Rust*, replacing cultivars susceptible to CLR with resistant ones requires large initial investments that most coffee producers cannot afford without economic support, while the replanted, young trees further stress financial conditions due to not producing harvestable cherries for at least 2 y (5, 11).

Additionally, coffee's genetic limitations have restricted the success of breeding resistant cultivars, and the rust itself has adapted to new cross-bred varieties. At least 50 races of *H. vastatrix* have been characterized and the pathogen continues to overcome host resistance (18, 40, 58), even if some sources of resistances have lasted more than 30 y (18). One of the last major breakdowns occurred in Honduras, where the resistance of the cultivar Lempira, released in 1998, was overcome by CLR following the high-intensity epidemics in 2012. Eleven new *H. vastatrix* races were identified in Honduras, seven of which were never detected before at a global level (40). The strategy of using resistant cultivars to curtail CLR may still be useful because many cultivars maintain partial resistance after complete resistance is overcome (59, 60). Colombia, for example, has adopted this approach. Since 2009, growers there have largely replanted with the Castillo variety, a CLR-resistant cultivar (61). By 2015, Colombia had more than 60% of its total coffee area planted with CLR-resistant cultivars (5). The development of new hybrid varieties like the F1 hybrids also offer promising prospects for building resilience in the global coffee sector. Among these new hybrids, some have demonstrated resistance to the rust disease, have a superior flavor, and can be grown under a wide range of production situations, including shaded conditions and at low altitudes with minimal to no problem. The F1 hybrids are the result of hybridizations between wild Ethiopian or Sudanese coffee plants and commercial varieties. Even when susceptible, they exhibit a good incomplete resistance (they have rust but not at high levels). They have two main problems, however: they are expensive, and they cannot be reproduced by seeds. Today, the hybrids are reproduced by in vitro techniques (although there are not many laboratories that do this) and by vegetative multiplication in specialized nurseries (as for multiplying trees). In summary, farmers cannot multiply these hybrids themselves. And the needs are so high that plants cannot be provided for everybody due to these reproduction limitations.

Due to the historical ability of *H. vastatrix* to overcome host resistance, coffee tree susceptibility to CLR is still likely to persist. CLR management deploying multiple control strategies at various points throughout the coffee-growing cycle has helped limit impacts. This includes the use of varieties with at least partial resistance, timely fungicide applications to reduce CLR inoculum, adequate nutrition to maintain plant health, and the use of shade cover to reduce a tree's fruit load and its exposure to solar radiation, thereby lowering its receptivity to the pathogen (9, 18, 23).

Coffee pest and disease surveillance programs are another important way to manage CLR. Many countries in Latin America implemented some form of monitoring after 2012. Surveillance systems—some with novel uses of smartphone apps—provide early warning to growers. Some forecast models have also been produced to add predictive features to the surveillance programs. However, several national systems have recently collapsed due to high costs and limited resources, and possibly a lack of tangible impacts.

Existing Approaches That the Coffee Industry and Farmers Use to Combat CLR Indirectly. Farmers, cooperatives, exporters, rural development agencies, and governments have also adopted indirect strategies to mitigate CLR impacts. These include: 1) adjusting global coffee industry sourcing to avoid reliance on rust impacted areas; 2) diversifying farms and livelihoods (62–65); 3) increasing prices paid to farmers and fostering more sustainable management, often through the use of sustainability certifications (e.g., organic and fair trade) (50, 66, 67) or by increasing domestic coffee consumption to increase demand, value added, and thus prices paid to farmers in coffee producing countries; and 4) collective action through farmer cooperatives and networked partnerships that aim to pool resources, share knowledge, access funding, and influence market governance (68–70). Some of these responses are short-term potential fixes. Others seek to address underlying structural issues, such as low resource endowments among smallholder farmers, high exposure to environmental hazards, and political economic variability (5, 6, 10, 71).

In the last 30 y, CLR outbreaks spurred social-ecological crises, with regional epidemics affecting hundreds of thousands of producers (5, 6). Two industry-led responses to maintain a global supply have included sourcing more coffee from countries unaffected by recent CRL outbreaks, like Brazil and Vietnam, and mitigating the pathogen by replacing susceptible coffee trees in impacted areas with resistant cultivars (43). As a result, worldwide coffee supplies continued to near-monotonically increase despite important production shocks (10).

Farm and livelihood diversification are also indirect strategies. Diversification reduces risks of economic loss by not being dependent on one or a few cash crops (64, 72). Diversification also differs between small-scale farmers and larger-scale plantations, with the latter being more specialized in coffee production and reliant on external inputs. Spatial diversification involves intercropping, planting multiple crops or varieties of the same crop, and growing shade trees (which can also produce fruit or become firewood and timber). Diversification in time includes cover cropping, and successional agroforestry systems that progress from mixed annual and perennial crops when the coffee bushes are young to multistrata shade coffee (73). The diversification of coffee varieties on a farm has not been widely reported as a CLR mitigation strategy, perhaps in part because it would bring tradeoffs related to commercialization and quality. In theory, however, varieties with greater resistance to CLR interspersed among others would seem to limit losses during CLR outbreaks. Carefully designed and effectively managed diversified farming can improve nutrient cycling and soil fertility—that in turn improve plant health—while also influencing CLR spread and potentially promoting biocontrol (24, 74). In Mexico and Central America, small-scale farmers have reported growing 25 to 50% of the food consumed in their households (6). Additionally, coffee smallholders that have diversified into subsistence crops, reported less food insecurity and less severe posthazard coping responses to drought and the CLR outbreak in Nicaragua (6). In addition to farm diversification, access to more land and higher incomes, which are often associated with diversified income sources and off-farm employment, correlate with improved household food security among coffee smallholders (6, 64, 75). However, there is no consensus on which diversification strategies are most likely to reduce risks in different settings, particularly in light of increasing challenging vulnerability contexts.

Differentiation through participation in niche coffee markets is another activity that may help farmers indirectly address CLR by securing market access, increasing farmgate price, and improving management. Organized farmers, roasters, and certification agencies have developed and rapidly scaled several eco-labels or sustainability certifications that aim to promote sustainable production and secure better economic returns to farmers. Certifications, such as organic, fair trade, Rainforest Alliance, and Utz, have proliferated and expanded since the late 1990s (67), together with accounting for more than 18% of coffee exports by 2014 (76). Claims about benefits of participation in these schemes have ranged from poverty alleviation and gendered empowerment to biodiversity and watershed protection. However, the evidence that attributes participation in certification programs to specific benefits in farmers' well-being, access to resources, improved farming practices, and more sustainable landscape management is context-dependent and mixed, depending on the certification, indicators, incentives, property rights, and more (77–79). Assessments of participation in selected certifications have found some correlation with improved farm management, the implementation of more environmentally friendly practices, higher farmgate prices, and access to more credit (80), all of which could contribute to healthier more CLR-resistant plants and faster recovery times from severe CLR episodes. The participation in these certification schemes is often linked to nongovernmental organization development assistance and frequently required by roasters and importers to maintain market access. However, the evidence from Latin America and elsewhere also suggests that participation in these schemes can be costly, may not deliver on higher net returns to coffee farmers, lead to significant additional improvements in crop management, or foster farmer empowerment and gender equity, and is insufficient to alleviate poverty in many cases, while farmer food insecurity remains a persistent challenge (79, 81).

Finally, cooperatives and other farmer associations are critical institutions that facilitate resource pooling, knowledge sharing, linking local actors with external agencies, participating in more of the value chain, and building political influence that can potentially shape national and international policies. In several places, including Nicaragua and Mexico, cooperatives and ejidos have assumed important historical roles in helping smallholders access land through a range of agrarian reform processes (82). Once acquired, these groups then try to maintain and invest in that land, offering not only agricultural assistance and links to markets, but also legal and political support to help secure land tenure, a critical asset that has correlated with additional investment and improved food security. There are examples of international aid agencies working with coffee institutes and co-ops to facilitate greater access to loans, CLR-resistant coffee plants, or crop insurance schemes (e.g., Costa Rica introduced new coffee insurance schemes in 2017), or involve farmers in monitoring pests in their farms through smartphone apps (e.g., Coffee Cloud in Guatemala). Accountable farmer co-ops or associations can also foster closer connections to coffee roasters, exporters, and development agencies to leverage funding for either improving coffee quality, replanting new varieties, or adjusting management strategies.

In sum, while there have been multiple direct and indirect responses to combat the threats posed by CLR, the results have been mixed. The systematic challenges in achieving large-scale uptake of introgressed varieties, the demonstrated ability of *H. vastatrix* to overcome host resistance, and the high costs or knowledge demands associated with chemical and biological controls have limited the impact of direct disease management approaches. Similarly, the systemic market volatilities that characterize the global coffee commodity chain have intersected with broader challenges of smallholder marginalization that have contributed to their social vulnerability. This has made it difficult for many coffee growing households to maintain a decent standard of living as rural poverty persists. These realities, we argue, require that we pay closer attention to proposals to transform the sector in order to address the underlying structural issues that render the sector vulnerable to social-ecological shocks.

Future Outlook

The ongoing socioeconomic disruptions caused by the COVID-19 pandemic pose a huge challenge for the global coffee industry. Declining global coffee consumption, farm labor shortages, and increasing production costs will negatively impact coffee harvests and investments in the sector, at least in the short term. There are growing fears that these disruptions will likely create conditions that could trigger another CLR epidemic that could further displace the livelihoods of millions of farmers and farmworkers in the Americas and other major coffee-growing regions. The impacts levied by the COVID-19 pandemic are unprecedented, but this moment also highlights the global coffee sector's fundamental susceptibility to recurring crises. It thus calls for transformational changes to deliver sustainable and equitable forms of resilience across the sector.

We contend that the direct and indirect approaches traditionally used to curtail social-ecological shocks like CLR are critical and necessary but have in the past been insufficient to develop viable and resilient livelihoods with many actors in the supply chain, most notably the small-scale producers. Therefore, what is needed are approaches and policies that are contextually rooted, socially just, equitable, and responsive to change. These include advancing research and monitoring activities on CLR to better understand the marginal effects of the different driving forces to which our paper has called attention. But, even more importantly, they should entail measures that address social vulnerability, poverty, and differential access to power, knowledge, and resources. We conclude by laying out three ways the coffee system can transform, recognizing that there is no panacea and that multiple strategies are needed, some of which we discussed above. These three issues relate to farmgate prices, institutional support, and the recognition that the quality, vitality, and prosperity of the coffee commodity chain depend on the strength of each link.

First, in terms of fiscal measures, farmers need to receive a minimum farmgate price sufficiently above the local cost of production in order to have economic security and the ability to invest in their production. Because the majority of smallholder farmers restrict their activities to only growing the coffee, they do not have vertically integrated operations and are thus excluded from most of the value chain. The trend, however, is for profits to concentrate in retailers and other actors higher up in the value chain. A minimum price would thus allow these farmers to capitalize more on favorable socioeconomic conditions, while at the same time better protecting them from losses during unfavorable periods. Certifications like fair trade have increased farmers profits in some cases, but they often fail to reach most farmers and are also subject to price variability (50).

We suggest that renewed regulation and a shorter value chain can increase returns for farmers. Implementing policies that guarantee an equitable distribution of income within the coffee value chain would improve livelihoods and the ability of farmers to respond to shocks like CLR. This has been done in Costa Rica with success, where the adoption of the Coffee Law (no. 2762) since 1961 and the establishment of the Instituto del Café de Costa Rica (ICAFE) guarantee a minimum price to farmers that is based on the sale price of coffee by hullers to exporters. Once some of the huller's costs have been deducted, producers may receive up to 91% of the remaining amount. All coffee-processing activities and sales in Costa Rica are regulated through the Coffee Law, which is intended to establish an equitable regime to regulate the relations between coffee producers, mills, and exporters. With respect to shortening the value chain, selling directly to consumers or roasters facilitates higher returns. While there are many barriers to instituting this—for example, coffee export licenses can be prohibitively expensive for smallholders—producer associations or cooperatives may help address some of the challenges.

The second way to transform the farming system is via increased institutional support, both at the state and international level. Decades of neoliberal policies favoring privatization, deregulation, and state retrenchment have reduced research, extension, and financial support for coffee farmers. The current pandemic highlights how vulnerable this approach has rendered the value chain. More robust partnerships between academic and research institutes, government agencies, farmer co-ops, and farmers of all sizes will make existing responses more effective, and likely lead to novel approaches. Rebuilding institutional support emphasizes the need for good governance and knowledge management. We have seen, for example, that countries with strong coffee institutes, such as Colombia's CENICAFE and Honduras's IHCAFE, have better faced CLR and recovered faster from crises than others that did not, such as Mexico or El Salvador, where mechanisms of dialogue between governments and producers were less available (11, 71).

Finally, we must also align coffee sector values with those that support sustainable agricultural economies. As multilateral organizations, governments, businesses, farmers, and civil society collaborate (and compete) to address pressing challenges, it is critical to recognize the key roles of labor and healthy functioning ecosystems in producing and sustaining profits. This means challenging current coffee value chains to better recognize the value produced by small-scale producers, while at the same time uplifting essential but underrecognized parts of the production process, such as human health, food security, and sustainability.

This last perspective is perhaps the enduring lesson of this pandemic. COVID-19 has shown that the health of individuals depends on collective health. Indeed, this is the underpinning logic in both public health and systems thinking. From one perspective, the interconnectedness of the global coffee system can be seen as a source of vulnerability. A shock will spread throughout the system, whether it begins within the coffee sector or the wider economy, and whether it is a zoonotic or plant disease, or a metaphorical financial contagion. From another perspective, though, this interconnectedness is also a source of strength. By treating coffee as both a community and a commodity, we give precedence to the health of the people and plants who produce it and their relations with each other. Doing so, though, requires a reckoning with the status quo. The spread of COVID-19 and CLR both reveal the systemic weaknesses and inequalities of our social and economic systems. We can thus only have a healthy coffee system by building up the well-being of the most vulnerable.

Data Availability. All study data are included in the article and *SI Appendix*.

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